DIRECT CONVERSION RECEIVERS (PART 1)

SOME NOTES ON DESIGN AND CONSTRUCTION TECHNIQUES

The direct conversion or synchrodyne receiver was invented several decades ago, but only with the advent of modern semiconductor technology has it come into its own as a viable design alternative. Although most designs are intended for novices, and lack certain features of high-grade superheterodyne receivers, the modern direct conversion receiver (DCR) is capable of exciting performance.

By Joseph J. Carr, B.Sc., MSEE

A case can be made for the assertion that the modern DCR is capable of performing as good as many middle grade communications receivers. Although that assertion may seem very bold indeed, the results of my literature search and experience building several different models bears it out. While no one, least of all this author, would represent the DCR as capable of the best possible performance, modern designs are no longer in the hobbiest curiosity category. In this two-part article you will find the basic theory of operation, some of the appropriate circuits, and some of the actual designs tried on the workbench.

Basic theory of operation

The DCR is similar to the superheterodyne in underlying concept: the receiver radio frequency (RF) signal is translated in frequency by nonlinear mixing with a local oscillator (LO) signal ('heterodyning'). **Figure 1** shows the basic block diagram for the 'front end' of both types of receiver. The mixer is a nonlinear element that combines the two signals, F_{RF} and F_{LO}. The output of the mixer contains a number of different frequencies that obey the relationship:

$$F_o = m\,F_{RF} \pm n\,F_{LO} \qquad [1]$$

Where:
F_o is the output frequency;
F_{RF} is the frequency of the received radio signal;
F_{LO} is the frequency produced by the local oscillator;
(All frequencies in same units).
m and n are integers (0, 1, 2, 3, ...).

All frequencies other than F_{RF} and F_{LO} are **product frequencies**. In general, we are only interested in the cases where m and n are either 0 or 1, so the output frequency spectrum of interest is limited

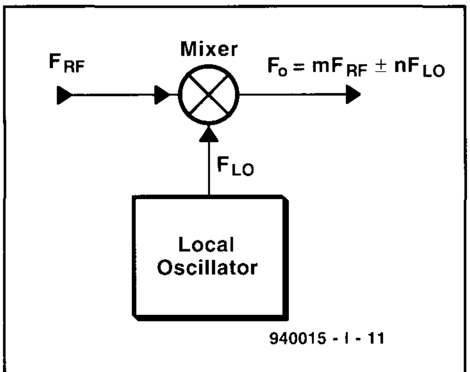


Fig. 1. Block diagram of the heterodyne frequency conversion circuit that forms the basis of both the superheterodyne and direct conversion receivers (DCR). In the DCR, $F_{LO} = F_{RF}$.

to F_{RF} and F_{LO} plus the product frequencies ($F_{RF}+F_{LO}$), and ($F_{RF}-F_{LO}$). The latter two are called **sum** and **difference intermediate frequencies** (IF). Other products are certainly present, but for purposes of this discussion are regarded as negligible.

In a superheterodyne radio receiver, a tuned bandpass filter will select either the sum IF or the difference IF, while rejecting the other IF, the LO and RF signals. Most of the gain (which helps determine sensitivity) and the selectivity of the receiver are accomplished at the IF frequency. In older receivers it was almost universally true that the difference IF frequency was selected (455 KHz and 460 KHz being very common), but in modern communications receivers either or both might be selected. For example, it is common to use a 9-MHz IF amplifier on high frequency (HF) band shortwave receivers. On bands below 9 MHz, the sum IF is selected while on bands above 9 MHz the difference IF is selected. A popular combination on amateur radio receivers uses a 9-MHz IF combined with a 5 to 5.5-MHz variable frequency oscillator. To receive the 75/80-meter band (3.5 to 4.0 MHz), the sum IF is used. The same combination of LO and IF frequencies will also receive the 20-meter (14.0 to 14.4 MHz) band if the difference IF (i.e., 14.0–5 = 9 MHz) is used.

In a DCR, on the other hand, only the difference IF frequency is used (see **Fig. 2**). Because the DCR LO operates at the same frequency as the RF carrier, or on a nearby frequency in the case of CW

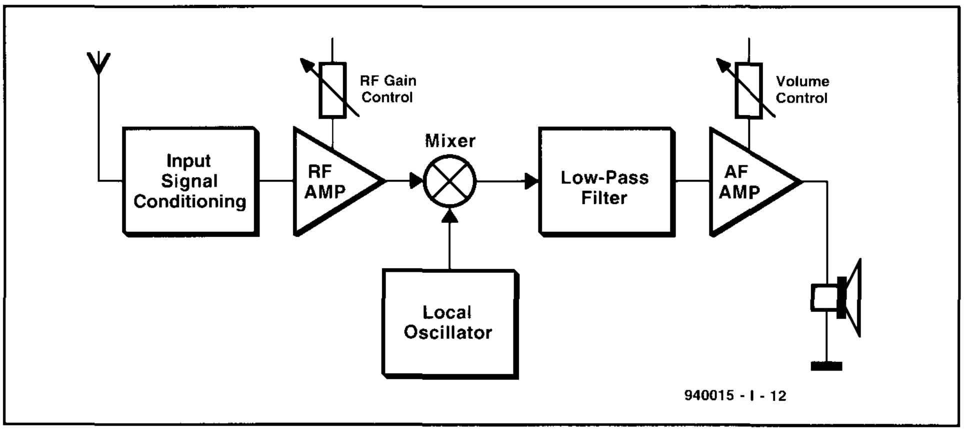


Fig. 2. Block diagram of a generic direct conversion receiver.

and SSB reception, the difference frequency represents the audio modulation of the radio signal. Amplitude modulated (AM) signals are accommodated by zero-beating the LO to the radio signal signal making $F_{LO} = F_{RF(carrier)}$. Thus, only the recovered upper and lower sidebands will pass through the system, and they are at audio frequency.

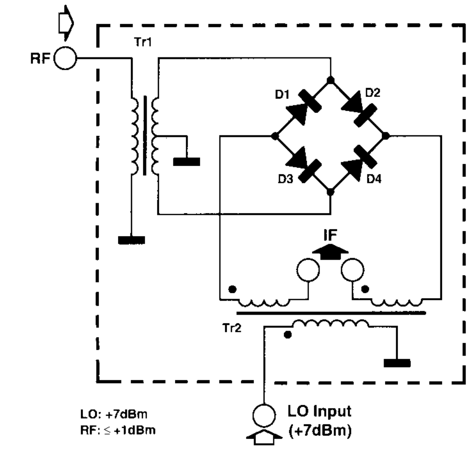
For CW signals (morse code on-off telegraphy), and single sideband signals, it is necessary to offset the LO frequency slightly to recover the signal. For the CW case one must select a comfortable tone (which is an individual preference). In my own case, I am most comfortable using an 800-Hz note when copying CW, so will offset the LO from the RF by 800 Hz. For example, when copying a CW signal at, say, 3650 KHz, the LO will be tuned to either 3649.2 KHz or 3650.8 KHz. In either case, the beat note heard in the output is 800 Hz. Single sideband (SSB) reception requires an offset of the order of 1.8 to 2.8 KHz for proper reception.

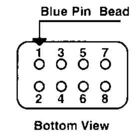
As was true in the superheterodyne receiver, most of the gain and selectivity in the DCR is provided by the stages after the first mixer. While the superheterodyne uses the IF amplifier chain for this purpose, followed by second detection and audio amplification, the DCR must use only the audio amplifier chain. Thus, it becomes necessary to provide some very high gain audio amplifiers and audio bandpass filtering in the DCR design.

One implication of DCR operation is the lack of single signal operation. Both CW and SSB signals will appear on **both** sides of the zero-beat point (F_{RF}=F_{LO} exactly). While this feature can be a problem, it has at least one charming attribute on SSB reception: the DCR will receive LSB signals on one side of zero-beat and USB signals on the other side of zero-beat. There have been attempts to provide single-signal reception of SSB signals on DCRs[1] by using audio and VFO phasing circuits (in the manner of the phasing method of SSB generation). That approach greatly increases the complexity of the receiver, which may make other design approaches more reasonable than DCRs.[2]

The most basic implementation of the DCR (**Fig. 2**) required only a mixer stage, a local oscillator and an audio amplifier. In fact, if the mixer has a high enough output signal level, and high impedance earphones are used to detect the audio, some designs can make do without the audio amplifier. These are, however, a rarity and the one version that I tried did not work very well.

In some DCR designs, there will be optional RF input signal conditioning consisting of either a low-pass filter, high-pass filter, or bandpass filter (as appropriate) to select the desired signal or reject undesired signals. Without some frequency selection at the front end, the mixer is wide open with respect to frequency, and may be unable to prevent some unwanted signal, or spurious combinations of signals, from entering the receiver circuits. Some designs will include more than one style of filter. For example, a popular combination uses a single staged tuned resonant circuit at the input of the mixer to select the RF signal to be received and a high-pass filter — with a cut-off frequency, F_{co}, of 2,200 KHz — which is designed to exclude AM broadcast band signals. The reason for such an arrangement is that the AM signal may be quite intense, being of local origin, and is therefore capable of overriding the minor selectivity provided by the tuned circuit.





Function	SRA - I SRA - I - I	SBL - I SBL - I - I	SBL - IX
Ground	2,5,6,7	2,5,6,7	2,5,6,7
LO In	8	8	8
RF In	1	1	3,4
IF Out	3,4 *	3,4 *	1

* Pins 3 + 4 to be connected together
Blue bead indicates Pin 1

940015 - I - 13

Fig. 3. Internal circuit of the SRA-1 and SBL-1 passive double balanced mixers. Inset shows pin-outs on device package.

The RF amplifier used in the front-end is also optional, and is used to provide extra gain, and possibly some selectivity. The gain is needed to overcome losses or inherent insensitivity in the mixer design. Not all mixers require the RF amplifier, so it is frequently deleted in published designs. In general, RF amplifiers are used only in DCRs operating above 14 MHz. Below 14 MHz, signals tend to be relatively strong and man-made noise tends to be much stronger than inherent mixer noise.[3]

Mixer circuits

The principal element in any direct conversion receiver (DCR) is the mixer. The mixer is a nonlinear circuit that exhibits changes of impedance over cyclical excursions of the input signals. When mixing linear, one signal will ride on the other as an algebraic sum, but the product frequencies are not generated. A mixer that produces product frequencies can be used either in DCRs or superheterodyne receivers. In superheterodyne receiver terminology it is common to call the frequency translation mixer that produces the IF a **first detector**, and the mixer that recovers the audio modulation either a product detector or **second detector**, even though the same type of circuit can be used for both cases.

There are any number of mixer circuits used in radio receivers, and most of them are candidates for use in direct conversion receivers. As you will see, however, not all mixers are created equal, so some are better suited to DCR applications than others. In nearly all cases, the output circuit of the mixer will be a low-pass filter that passes audio frequencies, but not RF frequencies.

Two issues seem to predominate mixer selection: **sensitivity** and **dynamic range**. The former determines how small a signal can be detected, while the latter determines the ratio between the minimum detectable signal and the maximum detectable signal. There are some passive mixers that produce so much loss, so much noise and require so much signal strength to operate in the first place that they are simply not suited to DCR design unless adequate preamplification is provided. Such detectors can sometimes be put to good use in superheterodyne receivers because they are preceded by the gain of the front-end and the IF amplfier chains, which can be considerable.

There are two issues that must be accounted for when selecting or building the mixer element of the DCR. First, there is always the possibility of radiation of the local oscillator (LO) signal through the antenna. In order to prevent this problem, it is necessary to keep the mixer unilateral, i.e. signal flowing only in one direction. Some mixers are inherently good in this respect, while others are a bit problematical. In cases where LO radiation might occur it is recommended that an RF amplifier be used ahead of the mixer, regardless of whether or not it is needed for purposes of improving sensitivity.

The second problem that must be rec-

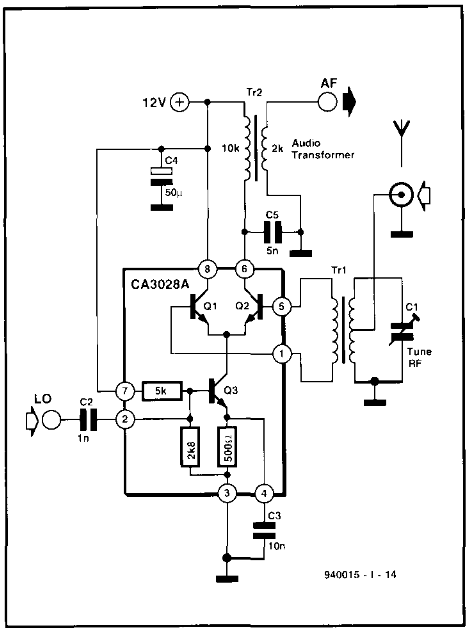


Fig. 4. Balanced mixer based on the CA-3028A IC device.

ognized is transmission of the RF or LO signals to the output of the mixer. Many forms of mixer are particularly bad in this respect, while others are considerably better. Theoretically any mixer can be used for the front-end of the DCR, however, the simple halfwave rectifier diode envelope detectors are not at all recommended.

Perhaps the best passive form of mixer is the **double balanced mixer** (DBM) of **Fig. 3**. This circuit provides superior suppression of the LO and RF signals in the output, leaving only the sum and difference IF frequencies. This type of mixer uses the same sort of diode ring circuit as the single balanced mixer discussed above, but adds a second transformer to the circuit for the RF signal. In this circuit, the LO signal is driven in push-pull across two opposite nodes of the diode ring, while the RF signal drives the alternate nodes in push-pull.

All of these diode mixers can be made with either hot carrier diodes (preferred) or ordinary silicon small-signal or switching diodes (those in the 1N914 and 1N4148 class are suitable). In either case, performance is improved if the diodes are matched. While matching is best done on an oscillographic curve tracer, silicon switching diodes can be crudely matched by comparing forward and reverse resistance readings obtained with an ohmmeter. Although not an optimal match, the resistance matching scheme results in superior performance over randomly selecting the diodes.

One of the most popular forms of commercial DBM is the **Mini-Circuits** (P.O. Box 166, Brooklyn, NY, 11235, USA; phone 718-934-4500) SRA-series and SBL-series devices. The pin pattern for the shielded case of these mixers is shown as an inset to **Fig. 3**, while the pin assignments are shown in the associated table. Note that pin 1 is indicated by a blue bead insulator around the pin, while the other pins will have a different color. Also, on the top of the mixer case the letters 'MCL' appear (which is the manufacturer's logo), and the 'M' is positioned directly above pin 2. These mixers are used in many published DCR designs, where they have proved an excellent choice. They are designed for 50-Ω input and output impedances, so are relatively easy to match with tuned circuits and *LC* filters. The RF signal must be kept at +1 dBm or below, while the LO signal must be around +7 dBm. At an impedance of 50 Ω, the +7-dBm signal level represents about 5 mW, or 500 mV_{rms} (1.4 V_{pp}).

An active mixer can be built with any of several different integrated circuits, or their discrete equivalents. One approach uses analog multiplier circuits, while another uses simple differential amplifier circuits. The mixer of **Fig. 4** is based on the CA-3028A differential IF/RF amplifier IC. The differential input impedance (pins 1 to 5) is of the order of 1 kΩ, while the differential output impedance (pins 6 to 8) is 8 kΩ. For an input circuit, therefore, a transformer is needed that converts the antenna impedance (typically 50 Ω) to 1000 Ω. This transformer can have a tapped primary that matches 50 Ω at the tap, while still providing tuning action to select input signals. The output network consists of an audio transformer with a 10-kΩ primary and a lower impedance secondary. The audio output of this circuit is quite low, despite being an active circuit, so it must be followed by considerable audio gain (80 to 100 dB).

Considerations for good DCR designs

It probably does not surprise many readers that there are some principles of good design that result in superior DCR performance. Some of these principles were discussed by Campbell[3] and others[4]. Even relatively simple DCR designs, including those based on the Signetics NE602 integrated circuit double balanced modulator[5] and the popular LM386 audio amplifier, have proven to be very sensitive and free of hum and microphonics, even though that combination is not without critics. Dillon's design, which was tested in the laboratories of the American Radio Relay League (ARRL), proved remarkably free of the problems often associated with simple DCR designs.[6]

One method for terminating the mixer is to place a resistor-capacitor (*RC*) network across the IF OUT terminals of the mixer and ground (see **Fig. 5**). The SBL-1 is designed for 50 Ω input and output impedances, so the device is terminated in it characteristic impedance at RF frequencies by the 51-Ω resistor (R1). Because capacitor C_1 has a value that produces a high reactance at audio frequencies (AF), and a low reactance at RF, the mixer is terminated for any residual LO and RF signal (which are absorbed by R_1), but AF is transmitted to the low-pass filter.

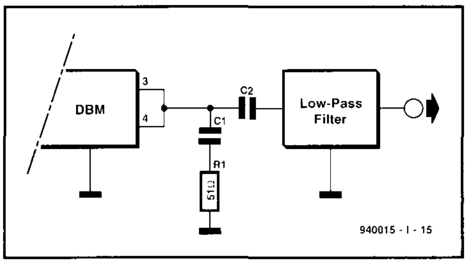


Fig. 5. Block diagram of mixer output circuit used in direct conversion receivers.

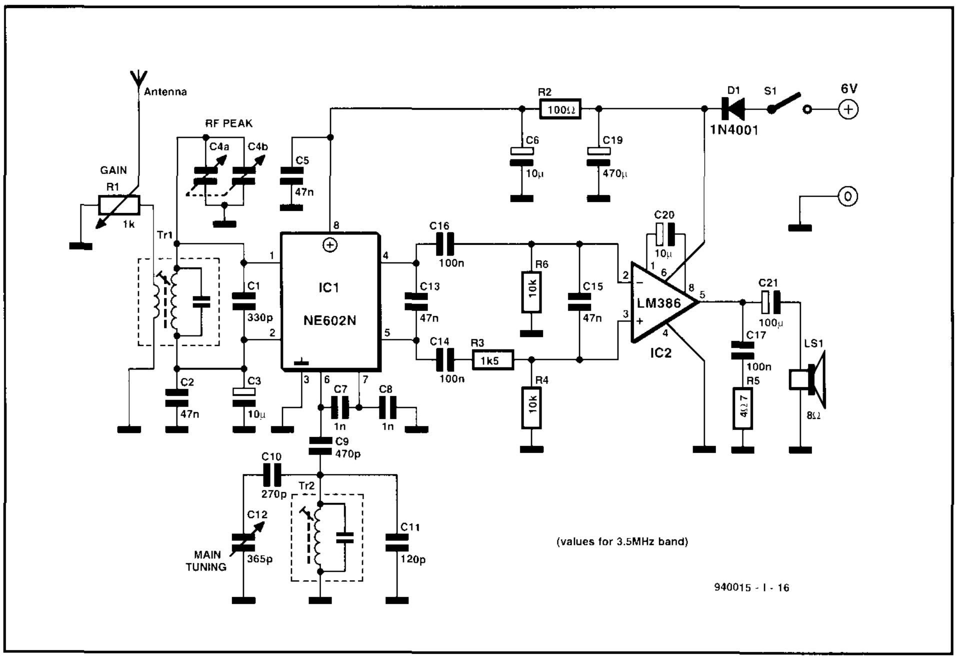


Fig. 6. Direct conversion H.F. receiver using the NE602 and LM386 integrated circuits.

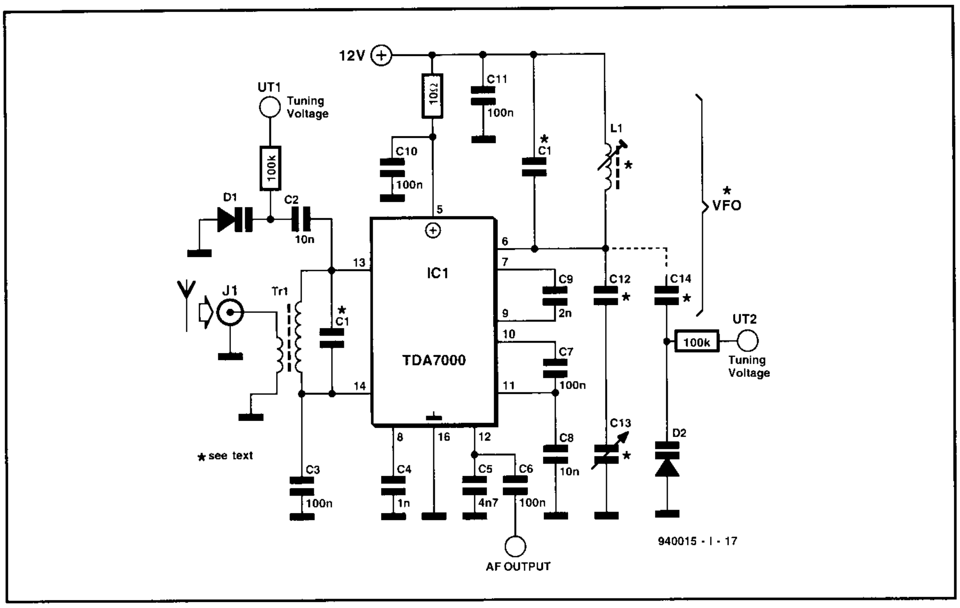


Fig. 7. Direct conversion receiver based on the TDA7000 integrated circuit.

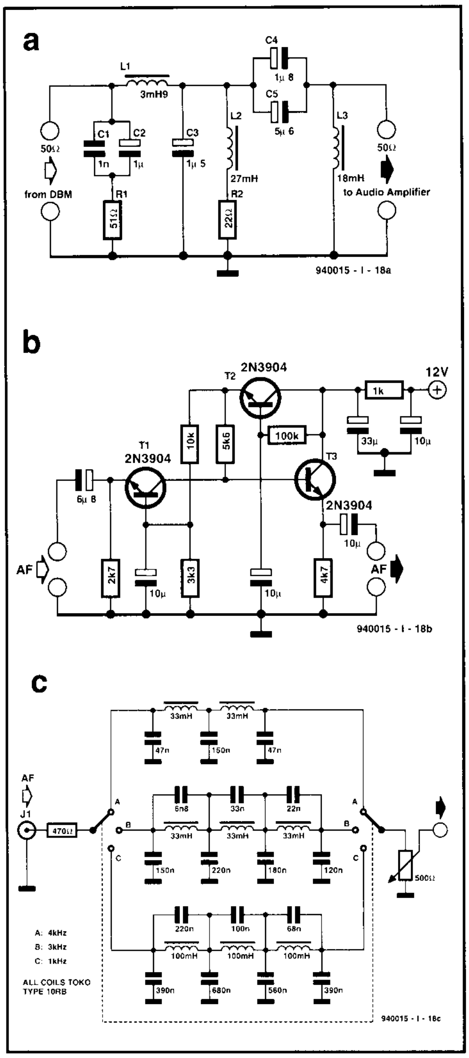


Fig. 8. a) Diplexer circuit used to terminate the mixer and filter the audio; b) audio preamplifier for direct conversion receiver; c) audio bandpass filters with three switch selectable bandpass characteristics.

Some practical design approaches

The NE602 type of DCR is relatively easy to build, and provides reasonable performance for little effort. The NE602 chip is relatively easy to obtain, and for the most part is well behaved in circuits (i.e. it does what it is supposed to do). It has about 20 dB of conversion gain, so can help overcome some circuit losses, and reduces slightly the amount of gain required of the audio amplifier that follows. The NE602 can provide very good sensitivity, on the order of 0.3 µV is relatively easy to obtain, but lacks something in dynamic range. Although the specifications of the device allow it to accept signals up to −15 dBm, at least one source recommended a maximum signal level of −25dBm[7]. At higher input signal levels, the NE602 tends to fall apart.[8] The newer NE612 is basically the same chip, but has improved dynamic range. While I have not personally tried the newer variety, it is reputed to be a greatly improved device compared to the NE602.

The Dillon design shown in **Fig. 6** uses the push-pull outputs of the NE602 (i.e. both pins 4 and 5), and is superior to the single-ended variety. According to Dillon, the balanced output approach improves the performance, especially in regard to AM BCB breakthrough. Also helping the breakthrough problem is the use of a 47-nF capacitor across the output terminals of the NE602.

Daulton takes exception to the use of the NE602 as the DCR front-end, and prefers instead to use the TDA7000 chip. While functionally similar to the NE602, the TDA7000 is more complex and is said to deliver superior performance with respect to dynamic range and signal overload characteristics. **Figure 7** shows a DCR front-end circuit based on the TDA7000 after Daulton's design. This circuit uses the same balanced front-end as other designs and, like the typical NE602 design, uses the internal oscillator for the variable frequency oscillator (VFO). The circuit following this front-end should be of the sort typically found in the NE602 designs. This particular variant uses the internal operational amplifiers of the TDA7000 to provide active bandpass filtering.

Figure 8a shows the passive diplexer used by Campbell[9]. It consists of several inductor, resistor and capacitor elements that form both low-pass and high-pass filter sections. The values of the inductors (L_1, L_2 and L_3) are selected with their d.c. resistance in mind, so it is important to use the originally specified components, or their **exact** equivalents in replicating the project. Campbell used Toko Type 10RB inductors: L_1 is a 181LY-392J, L_2 a 181LY-273J and L_3 a 181LY-273J.

The matched 50-Ω audio preamplifier is shown in **Fig. 8b**, and is an improved version of the Lewallen circuit. According to Campbell, this circuit provides about 40 dB of gain, and offers a noise figure of about 5 dB. The range of input signals that it will accommodate ranges from about 10 nV to 10 mV, without undue distortion. These specifications make the amplifier a good match to the DBM. Like the Lewallen circuit, the Campbell circuit uses a grounded base input amplifier (T_1), and an active decoupler (T_2). But Campbell also adds an emitter follower/buffer amplifier (T_3).

A set of three passive audio filters, which can be switched into or out of the circuit, is shown in **Fig. 8c**. These filters are designed for termination in an impedance of 500 Ω. Three different bandpasses are offered: 1 KHz, 3 KHz and 4 KHz. The 4-KHz filter is a fifth order Butterworth design, while the 3-KHz filter is a seventh order elliptical design after Niewiadomski[10]. The 1000 Hz design is scaled from the 3000 Hz design. Campbell claims that these filters offered a shape factor of 2.1:1, with an essentially flat passband "...with rounded corners, no ripple and no ringing."

Campbell implied the use of switching, as shown in **Fig. 8c**, but did not actually show the circuitry. As shown here, the switching involves use of a pair of ganged SP3P rotary switches. In a short time in the future I will be working on a PIN diode switched variant for a different purpose, and see no immediate reason why it shouldn't work.

A complex DCR was designed by Breed, and reported in the amateur radio literature as a direct conversion single sideband receiver.[1] The single sideband (SSB) mode is properly called **single sideband suppressed carrier amplitude modulation**, for it is a variant of AM that reduces the RF carrier and one of the two AM sidebands to negligible levels. This mode is used in HF transmissions because it reduces the bandwidth required by half, and removes the carrier that produces heterodyne squeels on the shortwave bands.

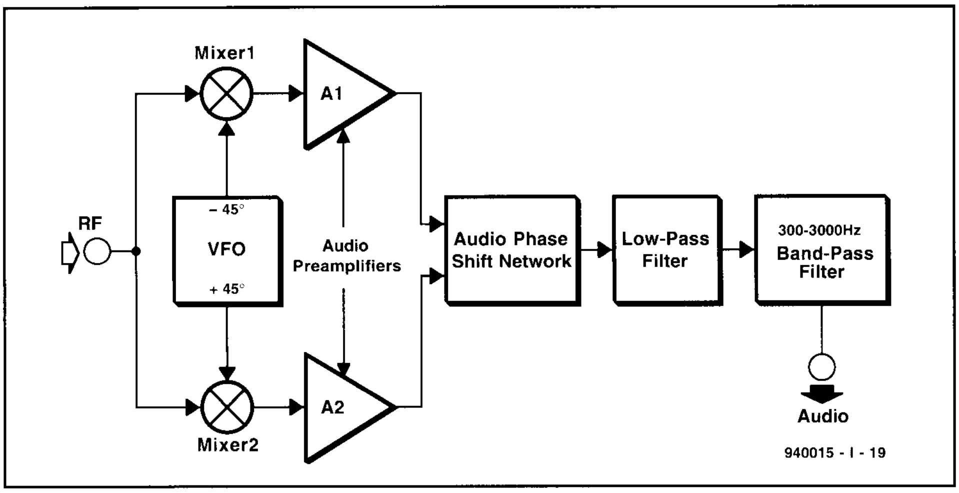


Fig. 9. Phasing-style direct conversion receiver for improved single sideband reception.

There are two methods for generating SSB. The most common today uses a double balanced modulator to combine a fixed carrier and the audio signal to produce a double sideband suppressed carrier output signal; the unneeded sideband is then removed by filtering. The older and more complex variant uses a phasing method of SSB generation. Breed uses the inverse process to demodulate SSB signals in a clever, but complex, receiver design (**Fig. 9**). This circuit splits the incoming RF signal into two components and then feeds them both to separate mixers. These mixers are driven 90 degrees out of phase by a VFO that produces –45° and +45° outputs. The respective outputs of the mixers are amplified and then fed to bilateral 90° audio phase shift networks where they are recombined. The output of the phase shift network is filtered in a low-pass filter and bandpass filter, to provide the recovered modulation.

Audio circuits

The audio chain in the direct conversion receiver tends to be very high gain in order to compensate for the low output levels usually found on the mixer circuits. The principal job of the audio amplifier is to increase the signal level by an amount that will create a comfortable listening level, while also tailoring the bandpass characteristics of the overall receiver to limit noise and other artifacts. Although any number of discrete and integrated circuit (IC) circuits are suitable, most designers today tend to use the IC versions. **Figure 10** shows a simple LM-386 design, while the published literature shows many other designs as well.[11]

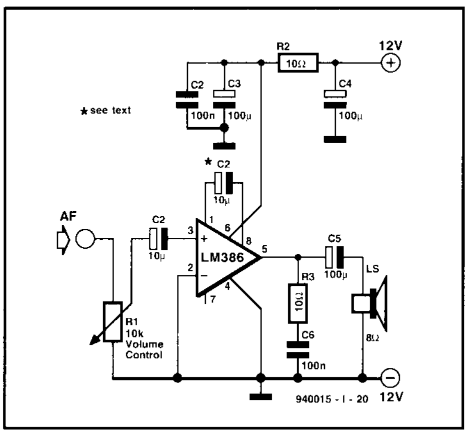


Fig. 10. Audio stage based on the LM386 audio integrated circuit.

The LM386 design of **Fig. 10** is the single-ended configuration for the LM386 low-power audio stage. This IC device contains both preamplifiers and power amplifiers for a nominal output power of 250 mW. The LM386 series of audio power ICs are easy to use, but because of the high gain needed will oscillate if layout is not correct, or if grounding is not proper. There are two basic circuit configurations for the LM386. The differential version was shown in **Fig. 6** (Dillon's design), while **Fig. 10** shows the more common single-ended design. The gain of the circuit can be either 46 dB (×200) when capacitor C_2 is used, or 26 dB (×20) when C_2 is deleted (leave pins 1 and 8 open-circuited).

Local oscillator circuits

The local oscillator (LO) for a continuously tunable receiver of any description is basically a variable frequency oscillator (VFO). Although higher grade receivers today typically use frequency synthesis techniques for generating the LO signal, the standard inductor-capacitor (*LC*) controlled VFO still has appeal for less complex receivers. The VFO used for the LO in receivers is pretty much the same as the VFO in transmitters, so transmitter VFOs are frequently used. There are some cases, however, where a receiver LO has at least one specification that is more rigid than the transmitter equivalent: many receivers have a requirement for low FM phase noise. In the main, however, amateur radio applications of direct conversion receivers typically use the transmitter VFO for the receiver as well.

Several different VFO designs are used for receiver LOs: Armstrong, Hartley, Colpitts/Clapp and an amplitude limiting design. The first three of these circuits are recognized according to the nature of their respective feedback networks, while the other is recognized by the special connection of a transformer. Note that the Colpitts and Clapp are basically the same circuit, except that the Colpitts uses a parallel tuned *LC* frequency setting network and a Clapp oscillator uses a series tuned *LC* network.

VFO circuits consist of an active element (transistor, IC, etc.) and a feedback network that must meet the **Barkhausen criteria** for feedback oscillators: 1) the loop gain of the circuit must be unity or greater, and 2) the feedback must be in-phase with the amplifier input signal. In most circuits, there is 180 degrees of phase inversion between input and output, so the feedback network must provide an additional 180 degrees at the desired frequency of oscillation. In practical terms, for HF VFO circuits these criteria result in a need for a gain-bandwidth product (F_t) in a bipolar transistor of 250 MHz or more and a gain (H_{fe}) greater than ten. The high F_t prevents unplanned phase changes at higher frequencies within the VFO range. For field effect transistors a transconductance of 2,000 siemens or more is usually required. In this article I have somewhat arbitrarily selected the

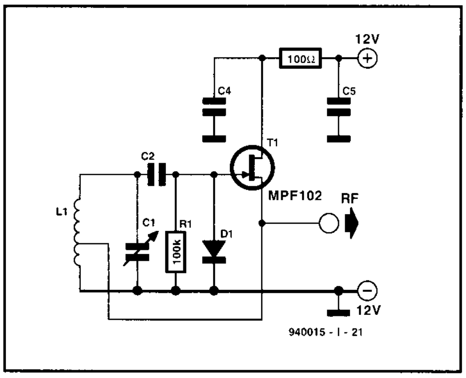


Fig. 11. Hartley VFO circuit.

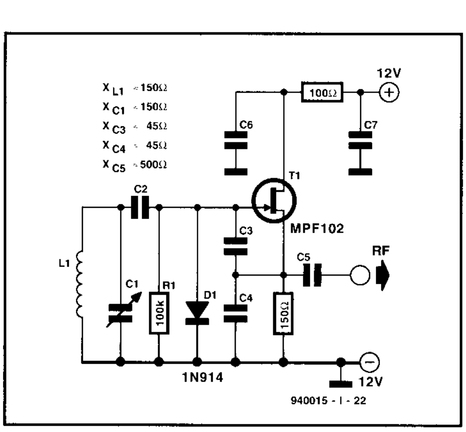


Fig. 12. Colpitts VFO circuit.

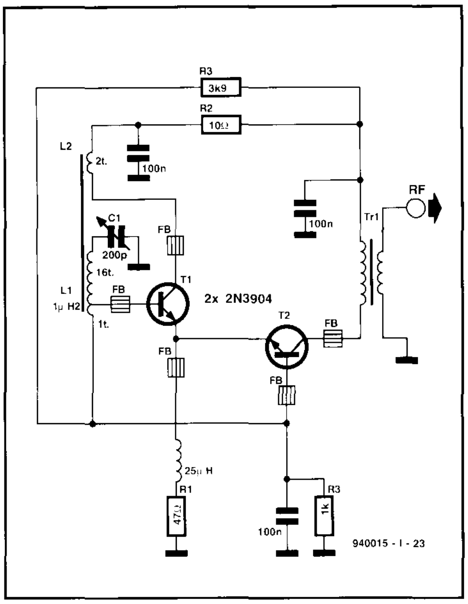


Fig. 13. Low-noise HF VFO circuit.

junction field effect transistor (JFET) of the MPF102 class to serve in the circuit illustrations. In addition, because the NE602 is so popular amongst DCR builders I have also included the three principle forms of oscillator circuit used with that chip: Hartley, Colpitts and Clapp.

Figure 11 shows a Hartley oscillator circuit. This type of oscillator is identified by use of a tapped inductor in the frequency setting network as part of the feedback network. The source of the JFET is connected to ground through the tap, so its current becomes the feedback signal. The top end of the coil is connected to the resonating capacitor and then to the gate of the JFET. Output can be taken from the drain, gate, or source terminals of the JFET, as well as from either a special tap on L_1 or a second winding on the same core as L_1. It is common practice to use a small value capacitor at the source terminal for output so as to lightly load the oscillator. The normal ideal is to have a capacitance that is large enough to permit fast starting every time the circuit is turned on, but small enough to not seriously load the LC network.

The tuned circuit that sets operating frequency consists of L_1 and C_1, with L_1 being tapped for feedback purposes. In most cases, the tap is between 20 and 40 percent of the total inductance. The coupling capacitor between the *LC* network and the JFET is a very small value so as to prevent loading. The diode in **Fig. 11** is used to provide a limitation on amplitude variations. This diode is a small signal silicon diode of the 1N914 or 1N4148 class.

Figure 12 shows the Colpitts VFO circuit. This circuit can be configured with a series resonant circuit, in which case it is called a Clapp oscillator. Both types of oscillator are identified by the tapped capacitor voltage divider providing feedback. The oscillating frequency is set by L_1-C_1, although the effects of C_2, C_3-C_4 and the gate capacitance of the JFET must also be considered.

Figure 13 shows a VFO circuit that uses the transformer core to provide output amplitude stability with a low-noise operation.[12] The inductor, which not only helps control frequency but also limits amplitude variations, is wound on an Amidon T-68-6 toroidal core. The main coil (L_1) consists of 17 turns of #26 AWG wire, and is tapped at 1 turn for the base of T_1. A feedback coil consists of 2 turns of the same wire on the same form.

Oscillator stability

Local oscillator stability is always important, but a case can made that it is more so in DCR receivers. Several factors are involved in VFO stability, and if these guidelines are followed result in a stable oscillator more often than not.[13] Some guidelines that will result in a more stable VFO are:

- Avoid excessive temperatures in the oscillator. Also avoid wide variation in temperature.
- Use only as much feedback as needed to ensure quick starting of the oscillator.
- Use an output buffer amplifier to isolate the VFO circuit from changes in the external load.
- Use an IC voltage regulator that serves only the oscillator device (but not the buffer amplifier).
- Rigidly mount the frequency determining capacitors and inductors.
- Prefer air core inductors over ferrite or powdered iron core inductors; prefer slug-tuned coils over toroids.
- Trimmer and main tuning capacitors should be air dielectric types, rather than mica or other materials.
- Small capacitors in the frequency determining network, or used as coupling from the frequency determining network, should be zero temperature coefficient types (NP0 disk ceramics preferred).
- Lightly load the frequency determining *LC* network by using a small capacitance (1-10 pF) between the tank circuit and the gate or base of the oscillator transistor.
- If an air variable capacitor is used for the main tuning control, then it should be a double bearing model.
- If a varactor diode is used for the main tuning control, then it should use a tuning voltage supply that is regulated by a varactor controller device such as the MVS-460-2/ZTK33B.

These guidelines are neither exhaustive nor absolute, but following them as closely as possible will result in a superior VFO stability.

In the second and final part of this article we will look at some practical designs of direct conversion receivers.

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4. Roy W. Lewallen, W7EL, 'An Optimized QRP Transceiver', *QST* August 1980, pp. 14-19; Paul G. Daulton, K5WMS, 'The explorer: HF Receiver for 40 and 80 meters', *73 Amateur Radio Today* August 1992, pp.30-34; John Dillon, WA3RNC, 'The Beophyte Receiver', *QST* February 1988, pp. 14-18.

5. Micheal A. Covington, 'Single-chip Frequency Converter', *Radio Electronics* April 1990, pp. 49-52; Joseph J. Carr, 'NE602 Primer', *Elektor Electronics* January 1992, pp. 20-25.

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11. Ray Marston, 'Audio Amplifier ICs', *Radio-Electronics*. April 1990, pp. 53-57. See also the *National Semiconductor Linear Data Books*, or the data books of other major IC manufacturers for applications information and device data.

12. From an article by L. Gunn, K7HFD, discussed and cited in W. Hayward and D. DeMaw, *Solid-State Design for the Radio Amateur*, American Radio Relay League (Newington, CT, USA, 1977).

13. These criteria were developed from W. Hayward and D. DeMaw, *Solid-State Design for the Radio Amateur (op-cit.)*.

DIRECT CONVERSION RECEIVERS

PART 2 (final)

SOME NOTES ON DESIGN AND CONSTRUCTION TECHNIQUES, AND THREE PRACTICAL EXAMPLES

By Joseph J. Carr, B.Sc., MSEE

In the previous instalment of this article we examined the theory behind direct conversion receivers (DCR). In this final instalment we will take a look at three simple projects that are based on the principles discussed in Part 1. Three different designs are selected for testing: the 40 and 75/80-meter bands 'Neophyte' design by John Dillon[1]; a 40-meter band HF receiver based on the passive DBM designs of Lewallen and Campbell[2]; and a VLF design. All three designs were fabricated and tested on a common test chassis built especially for the purpose.

The common test chassis

Part of the decision to build and test several direct conversion receivers involved having a common chassis for all three designs. Although not very elegant, being made of scrap aluminum chassis and bottom plates from the 'junk box', it was at least low cost and effective. **Figure 1** shows the receiver test bed front panel. It is fitted with a Jackson Brothers calibrated dial with a 10:1 fast/slow vernier drive. The 6.35-mm (0.25-in.) shaft coupling on the vernier drive is used to turn either a variable air dielectric capacitor or potentiometer, depending on whether the DCR being built is a mechanically tuned or voltage tuned version. For most of the experiments the voltage tuned variety was used. Two additional controls are also provided, and both are potentiometers. The pot to the right of the tuning knob is a volume control, while that to the left is the RF tuning control (for voltage tuned front-end circuits).

Three circuits are provided for the test bed: two d.c. power supplies and an LM386 audio power amplifier. One d.c. power supply (**Fig. 2**) is used to provide +12 V regulated to the circuits of the DCRs used on the test bed. It uses a 7812 three-terminal IC voltage regulator, and works from a 15 Vd.c., or higher source. In the case of this project, raw power was provided by two 9-V dry-cell batteries connected in series. The second d.c. power supply (**Fig. 3**) consists of a 78L12 low-power, three-terminal voltage regulator and a potentiometer. The potentiometer is for main tuning, and is ganged to the main dial of the chassis. In normal use, this potentiometer is used to tune the local oscillator (LO) of the DCR.

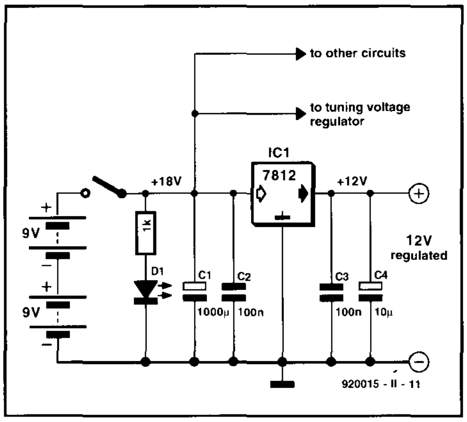


Fig. 2. DC power supply for the DCR test chassis. A pair of 9 volt batteries provides primary power, which is then regulated to 12 V by a 7812 IC voltage regulator.

The audio amplifier is the LM386 low-power 'audio system on a chip' device. The LM386 uses a minimum of external components, and includes both the audio preamplifiers and the power amplifiers to produce between 250 mW and 700 mW of audio power, depending on the particular device specified. The circuit for the audio section is shown in **Fig. 4**, while its location on the test bed chassis is shown in **Fig. 5**. Note that the audio section has its own +12-V regulator. This is an optional feature, but does serve to keep load variations in the audio amplifier from coupling to the rest of the circuitry. The audio section is the small circuit board on the left side of the chassis right by the audio volume control.

Figure 5 shows the rear view of the DCR test bed chassis. As mentioned, the audio amplifier section is shown on the left. The gray metal box contains either the variable air-dielectric capacitor, or potentiometer and power supply (**Fig. 3**),

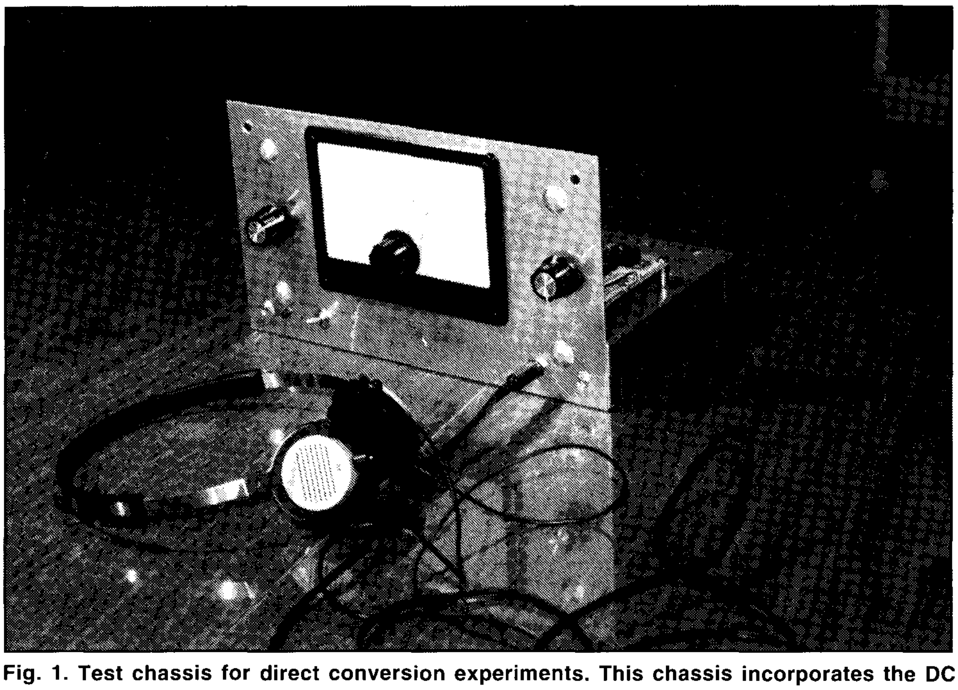


Fig. 1. Test chassis for direct conversion experiments. This chassis incorporates the DC power supplies, tuning voltages for RF and LO, and an LM386 audio amplifier stage.

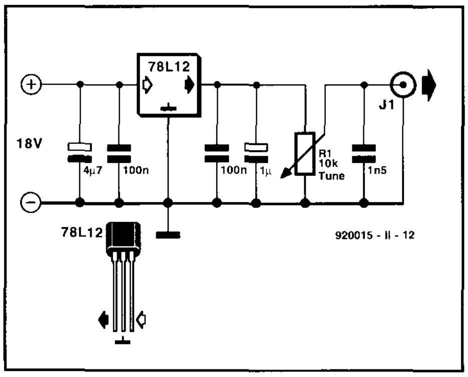


Fig. 3. Tuning voltage source. Potentiometer R1 is mechanically ganged to the main tuning dial and gear assembly.

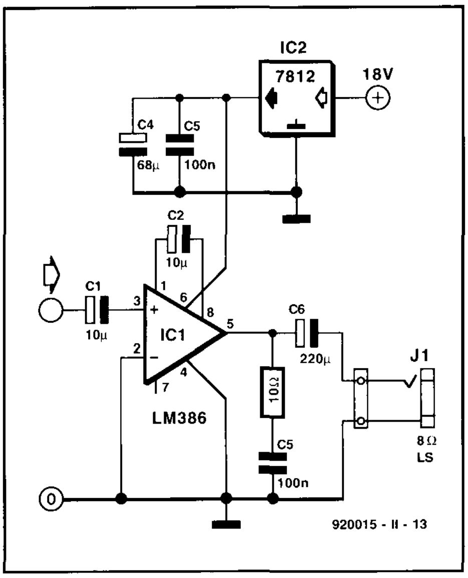


Fig. 4. Circuit for the LM386 audio amplifier stage on the DCR test chassis.

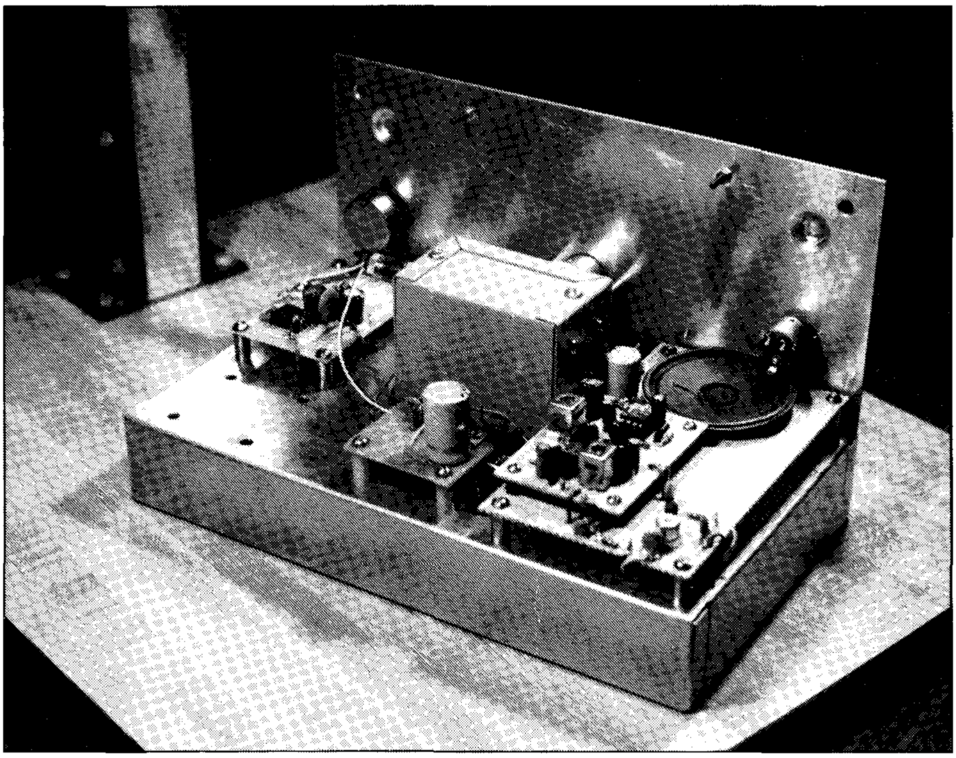


Fig. 5. Rear view of the DCR test chassis. Audio stage is on the left side, while the tuning voltage circuit is within the shielded metal enclosure. The main voltage regulator is behind the tuning voltage box (main batteries beneath chassis). Each test receiver was fabricated on a piece of perforated circuit board (shown here with the Dillon receiver mounted). In this example the audio stage was not needed because it was incorporated in the commercial printed circuit board mounted to the receiver board.

either of which may be used to tune the local oscillator of the DCRs being tested. The 12-V d.c. power supply is located on the small printed circuit board to the rear of the tuning box. Space is provided to the right of the tuning box for the circuitry of the DCR being tested. This board is changed from one project to the other.

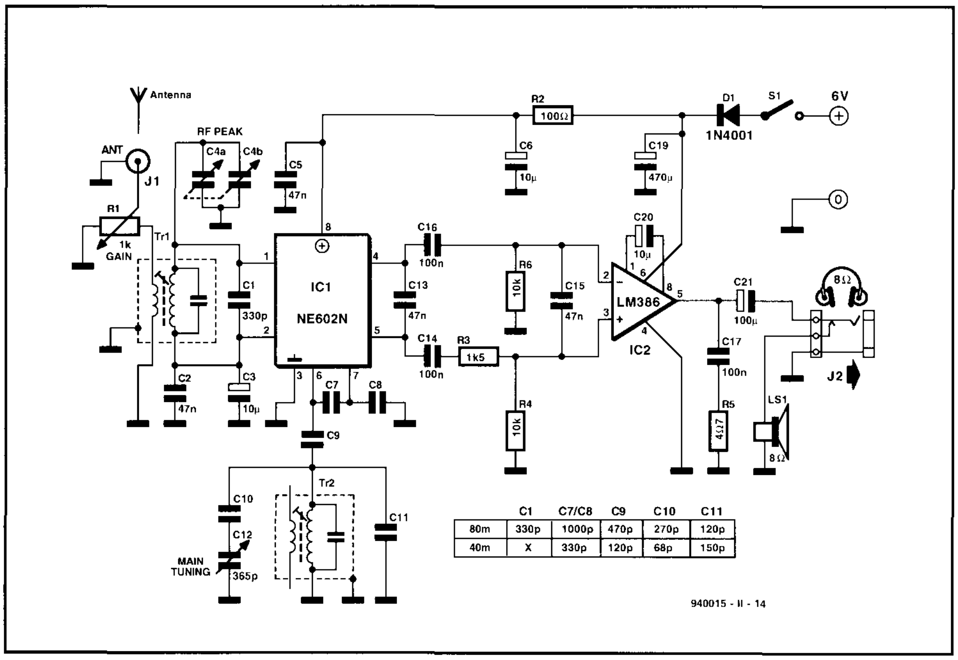
Wiring board construction used two different methods. The audio amplifier, the tuning d.c. power supply and 12-V d.c. regulated power supply were built on Radio Shack (Tandy) 'universal' printed circuit boards. The DCRs, on the other hand, were wired using Vector perfboard with a hole grid on 0.1-inch centres, or an equivalent product.

Three different antennas were used for testing the DCRs in this article: a 5BTV Cushcraft ½-wavelength ham band vertical, an outdoor 30-m (100-ft) random length end-fed wire, and a 6-m (20-ft) wire strung across the ceiling of my basement workshop. Interestingly enough, on the HF bands there was not a large difference between the outdoor antennas' performance and only slightly more difference between the outdoor antennas and the indoor antenna. On the VLF band, however, the random length wire was clearly superior to the other two antennas.

75/80 and 40-m NE602 design

The first DCR tested is the John Dillon design, which was originally published in *QST*[3] and discussed in Part 1 of this article. The Dillon design is based on the Signetics NE602 frequency converter chip available in the form of a parts kit from PennTek Electronics in the USA (14 Peace Drive, Lewistown, PA 17044, USA; Phone: 717-248-2507 — overseas callers note: normally a recording answers). The kit contains a printed circuit board and all of the electrical parts needed to build the receiver except for the variable capacitors. These capacitors are becoming difficult to obtain in the USA, but the Maplin (P.O. Box 777, Rayleigh, Essex, SS6 8LU, UK; phone 0702 554171) catalogue in UK offers several reasonable candidates for both RF and LO tuning capacitors.

The circuit for the Dillon design is shown in **Fig. 6**. The RF 'heart' of the circuit is the NE602 converter chip. The NE602 contains the local oscillator (LO) and a transistor double-balanced mixer (DBM) in the form of a transconductance cell. This design provides about 20 dB of conversion gain, good sensitivity, and rejection of the LO and RF signal components in the output. However, the early design chip is a little lacking in dynamic range (a problem reputedly corrected in the updated NE612 chip). The Dillon DCR



	C1	C7/C8	C9	C10	C11
80m	330p	1000p	470p	270p	120p
40m	X	330p	120p	68p	150p

Fig. 6. Circuit for the Dillon H.F. DCR.

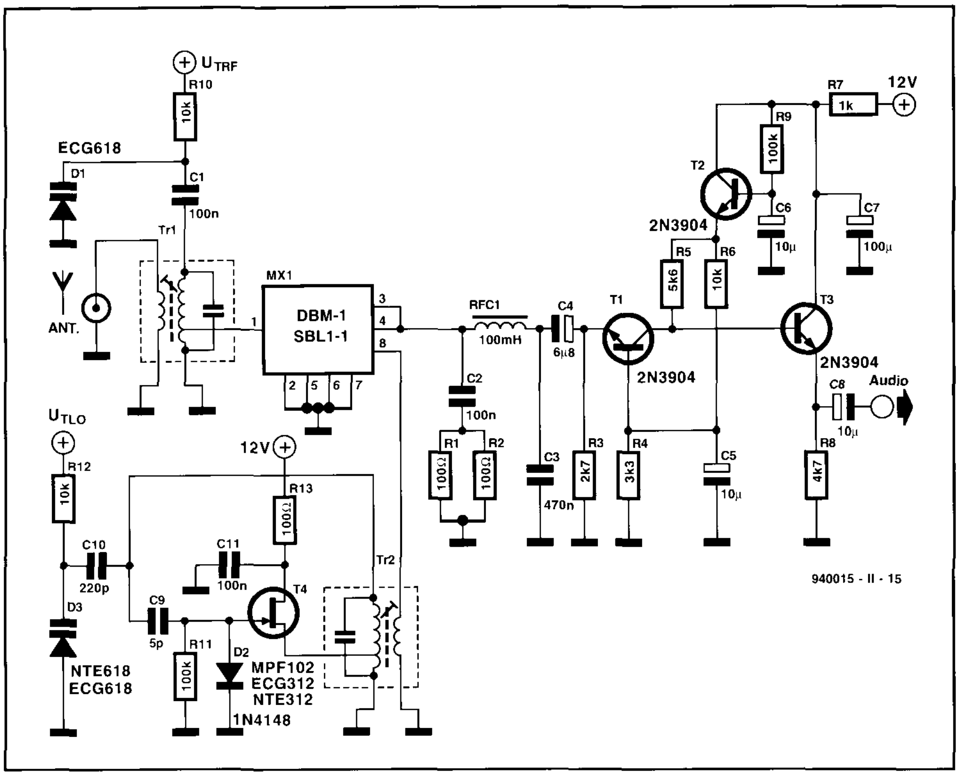


Fig. 7. DCR design based on a commercial passive double balanced mixer (DBM).

uses the balanced outputs of the NE602 (most designs are single-ended) in an effort to improve AM rejection. Likewise, to match the NE602 output scheme, the LM386 audio amplifier is wired in the differential input configuration.

Dillon's commercially produced printed circuit board was mounted on a piece of perf-board (see **Fig. 5** again) that was cut to fit the space available on the test bed chassis. In addition to the Dillon board, the perf-board contained the circuitry for the RF and LO varactor circuits and a 7806 three-terminal voltage regulator to reduce the 12 V available on the test bed to the 6 V specified by Dillon.

The Dillon receiver can be used on either 75/80 meters, or 40 meters, depending on how the oscillator is configured. The performance is optimized for 75/80 meters, according to Dillon. In a telephone conversation John Dillon told the author that the 40-meter band was added later in accordance with the wishes of the original publisher of the project. However, despite Dillon's reservations, I found the 40-meter performance to be about the same as the 75/80 meter performance with the possible exception of overload problems due to the high power AM signals from international broadcasters found in the 40-meter band.

The Dillon design proved to be remarkably sensitive, much more so than I anticipated. Perhaps that is an advantage of the 20-dB conversion gain of the NE602.

Criticisms of the design include two things related to the audio amplifier.

First, there is no volume control. The level of the output signal is controlled by a 1000-Ω linear taper potentiometer that varies antenna signal to the RF front-end. I found the lack of a volume control disconcerting, but not overwhelmingly so.

Second, there is a general criticism of this design and all other designs I built where the LM386 is used alone for the audio stage without preamplification. The audio gain is insufficient to provide for really comfortable listening, especially when a loudspeaker was used instead of earphones. I believe that this could be relieved by adding a preamplifier stage ahead of the LM386. If the differential nature of the circuit is to be preserved, then an operational amplifier can be used for this purpose. Several candidate op-amps (or operational transconductance amplifiers) are available that work well on single polarity d.c. power supplies.

A crude test of this theory proved interesting. I attenuated the output of Dillon's receiver with a 1000-Ω potentiometer to make it compatible with the input of the LM386 audio amplifier that is used in the DCR test bed. The total gain of the two LM386s, even with some attenuation, was considerably higher than the gain of the receiver circuit alone. The result was loud and clear signals that would not tax a middle-aged, hard of hearing guy like me. Dillon confirmed the lack of audio gain[5]. He told me that he had designed a three-IC version that inserted a dual op-amp between the NE602 and LM386 (one section was a preamplifier and the other an audio filter). He stated that the present design was selected because of a goal of two-IC simplicity.

My general assessment of the Dillon design is that it makes a decent weekend project for anyone who wishes to experiment with direct conversion radio receivers. The receiver can be used as designed, or easily modified if that is your preference. It is easy to modify for bands other than the amateur radio bands because both its circuitry and mechanical implementation are straight forward. It also provides a basis for experimenting with other variations of the basic design.

High-frequency DCR based on passive DBM

The next receiver that I built and tested was a high frequency design based on the MiniCircuits (P.O. Box 350166, Brooklyn, NY, 11235-0003, USA; phone 718-934-4500) SBL-1-1 passive double-balanced mixer (DBM). This mixer device provides frequency conversion up to 500 MHz, at LO power levels up to +7 dBm and RF levels up to +1 dBm. For higher dynamic range performance, there are variants that accept higher levels in both the LO and RF ports. The cost of those devices, however, is also higher than the SBL-1-1. If the SBL-1-1 is not easily available, then substitute the SRA-1 or SBL-1 designs. Alternatively, it is relatively easy to achieve reasonable performance using a homebrew passive DBM (see Part 1 of this series). Such circuits use toroidal coupling transformers and hot carrier RF diodes for mixing. The RF signal is applied to pin 1 of either SRA-1 or SBL-1 devices, while the LO is applied to pin no. 8; pins 2, 5, 7 and 8 are grounded. The IF output is found on pins 3 and 4, and these pins must be connected together for proper operation.

The circuit for this receiver is shown in **Fig. 7**. The circuit was built on a piece of perf-board cut to fit the space available on the test bed. The RF front-end of the receiver consists of a 10.7-MHz IF transformer intended for FM transistor radios; a Mouser Electronics (2401 Highway 287 N, Mansfield, TX, 76063, USA; phone 817-483-4422) type 42IF123 was used. FM IF transformers are a little broad banded (>200 KHz) for this application, but are convenient. A higher *Q*, narrower band transformer can be built if desired.

Another problem with the 10.7-MHz IF transformer is that the tap is not a good match to 50 Ω because the tap seems to be at a point where the impedance is apparently a couple of hundred ohms. However, the mismatch did not deteriorate the performance so much that it overcame the convenience of the easy-to-obtain transformer. Optimization of the circuit requires an RF transformer designed with a 50-Ω tap.

The internal capacitor of the IF transformer can be disconnected if desired, although I used it as part of the tuning capacitance for the circuit. At frequencies higher than 11 MHz, however, the

capacitor will have to be removed. This capacitor is found in a small external recess in the base of the IF transformer. It is not easy to 'disconnect' the capacitor without a lot of work and potential damage to the transformer. The best way to get rid of the capacitor is to crush it with a small probe or screwdriver tip. Be sure to remove the debris to keep it from shorting other circuits.

The circuit as shown will tune from about 5 MHz to greater than 9 MHz when the 440-pF varactor is used. The total capacitance seen by the transformer secondary consists of the internal capacitor (unless removed) plus the combined capacitance of C_1 and D_1. This capacitance is:

$$C_{TRF} = (C_1 C_{D1}) / (C_1 + C_{D1}) \qquad [2]$$

You can change the range of the tuning by using other values of capacitance than the 10 nF shown. When the 10-nF capacitor is used, the total capacitance is very nearly the capacitance of the diode. Other implementations of C_1 can include combinations of smaller valued fixed and variable (trimmer) capacitors.

The local oscillator for the receiver is a JFET Hartley oscillator that uses the same type of IF transformer as the RF input circuitry for main tuning. The secondary of the transformer is tuned to 10.7 MHz initially, but this frequency is modified by the external varactor circuit. The particular transformer used must be evaluated so that the tap is closer to the grounded end than the gate end of the winding. I found the correct configuration by simple comparison of the d.c. resistance of the segments of the winding (B-A and B-C) referenced to the tap (0.3 Ω and 0.8Ω , respectively). This type of circuit was discussed in Part 1 of this article.

The tuning varactor has a maximum capacitance of 440 pF, but this value is a bit large for practical use. Therefore, a series capacitance, which is needed for d.c. blocking in any instance, is used to reduce the total capacitance. The same formula as above can be used for determining the value of series capacitance needed for making the circuit tune to any particular range.

The d.c. power supply was the same 12-V supply as used for the rest of the circuitry. An improved version might use a +9-V regulator to supply only the oscillator transistor. This design would prevent frequency pulling due to power supply noise or voltage variations caused by shifts in load current. If the receiver had used an incorporated audio power amplifier, rather than the outboard style used here (which has its own 12-V regulator), a separate regulator would have been indicated.

The output signal, when a 12-V d.c. power supply was used, was of the order of 800 mV_{pp}, so is within the drive range permitted by the SBL-1-1.

The IF output of the DBM (pins 3 and 4) is terminated in two circuits. First is capacitor C_2 and resistors R_1 and R_2. This network forms a 50-Ω match to the 50-Ω output of the DBM for high frequencies (a function of the capacitor). The $C_2/R_1/R_2$ network absorbs any residual LO and RF signal that makes it past the conversion process, while allowing the mixer to operate into its characteristic impedance. The second circuit terminating the DBM is an audio *LC* low-pass filter consisting of RFC_1 and C_3. This circuit passes only those audio frequencies in the normal communications audio bandwidth below 3 KHz.

The audio preamplifier for the receiver is a two-stage amplifier based on common n-p-n bipolar transistors (2N3904 or equivalent). Transistor T_1 is a common base amplifier. It is used because its low input impedance is a reasonable match to the filter and DBM. Transistor T_3 forms an emitter follower output amplifier. An active decoupler (T_2) is used in the power supply line of the amplifier.

Like the other receivers, this design suffered from a lack of audio gain, although this defect was without practical effect when only headphones were used for reception. If you would like to try improving the circuit, then try using an IC audio preamplifier between the output of T_3 and the input of the audio power amplifier stage. Also, a higher power audio amplifier might prove useful.

VLF direct conversion receiver

The very low frequency (VLF) bands are those frequencies below the medium wave AM broadcast band, i.e., below 540 KHz. A considerable amount of CW (morse code) and radio beacon activity is found in the VLF bands all over the world. In Europe, there is another broadcast band in the VLF region (145-280 KHz).

The circuit for the VLF DCR is shown in **Fig. 8**. This design is similar to Dillon, and also to one published in *The ARRL Handbook for Radio Amateurs (1993 Edition)*[6], although a number of component values are changed because of the changed frequency range.

The front-end of the circuit is an NE602 integrated circuit. In the test circuit, the input circuit is untuned, although tuning can be accomplished by connecting a capacitor from point 'A' in Fig. 8 to ground. Most readers will probably wish to use a combination of a varactor diode and a parallel fixed capacitor, rather than an actual air variable capacitor, as shown in the inset to **Fig. 8**. The capacitor marked C_x can be used to ensure the tuning range of the varactor and T_1.

The RF input transformer (Tr_1) and the local oscillator inductor (Tr_2) are 0.63-mH transformers intended for use as 455-KHz IF transformers. I used Toko RAN-10A6845EK, available in North America from Digi-Key (P.O. Box 677, Thief River Falls, MN 56701-0677; USA: Phone 1-800-344-4539 in USA and Canada) as part no. TK-1202.

The local oscillator circuit connected to pins 6 and 7 is a straightforward series-tuned Colpitts or Clapp design using the inductance of a 455-KHz IF transformer (see above) and a 440-pF voltage variable capacitance diode ('varactor'). I used the NTE618 or ECG618 service re-

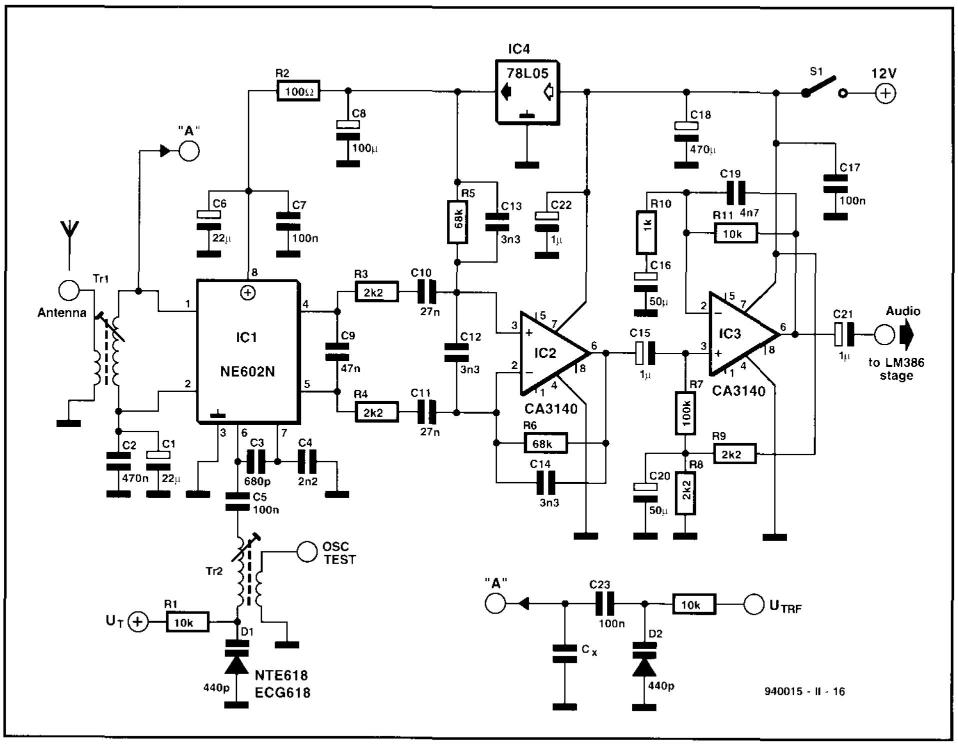


Fig. 8. Circuit for the VLF DCR receiver.

placement types for this receiver.

A feature of using an IF transformer for the LO tuning coil is that the secondary of the coil can be used as a test point ('OSC TEST') for measuring the oscillator frequency.

The output network of the NE602 is the differential form seen in Dillon earlier. A 47-nF capacitor is connected across output pins 4 and 5 for AM and LO/RF suppression. A differential operational amplifier (IC_2) is used as an audio preamplifier to boost the signal level about 30 dB. The output of this amplifier is coupled through C_{15} to a non-inverting amplifer with a gain of 11. This stage was initially not used, but the audio output proved to be lower than I deemed comfortable when fed directly to the LM386 amplifier on the main chassis.

Both operational amplifiers are type CA3140 BiMOS devices, although it must be mentioned that the selection was based on supplies on-hand. There is no reason why any garden-grade op-amp would not work (the required audio bandwidth is only 3,000 Hz for SSB and even less for CW). A common 741 (which shares the pin-outs of the CA3140), or any other common op-amp will do nicely. Keep in mind, however, that the capacitors from pin no. 7 of both IC_2 and IC_3 are absolutely mandatory if CA3140 devices are used, and they must be connected as close to the body of the amplifier as possible.

The d.c. power distribution in this circuit is simple and straightforward. The +12 V supply voltage is applied directly to IC_2 and IC_3, which are both wired in the 'single-supply' configuration. In the case of IC_2 the amplifier is differential, so one of the resistors goes to +5 V rather than to ground, as is usual in such amplifiers. In the case of IC_3 there is a resistor voltage divider (R_8/R_9) used to bias the non-inverting input. Because of this form of operation, there will be a potential of about +6 V at output pin 6, so as a result a coupling capacitor (C_{21}) is needed to prevent interaction with the following stages.

This circuit performed reasonably well, but I felt that it lacked some of the sensitivity seen in the high frequency versions. In addition, there was severe interference from AM broadcast band signals at 560 KHz, 630 KHz and 1220 KHz (which station is very close to my home). A VLF RF preamplifier and proper shielding of both circuits solved the problem. I still intend to experiment with low-pass filters set to attenuate signals above 520 KHz as a means for eliminating the AM signals.

Conclusion

In the two instalments of this article we have toured the world of direct conversion receivers, examined their weaknesses and strengths and provided some examples of both circuit elements and complete circuits. What is left is for you to design and build a version of your own. ■

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4. 'NE602 Primer', Jospeh J. Carr, *Elektor Electronics*, January 1992, pp. 20-25.
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